J. agric. Sci., Camb. (1971), **76**, 539–552
With 3 text-figures
Printed in Great Britain

Potassium in soils under different cropping systems

1. Behaviour of K remaining in soils from classical and rotation experiments at Rothamsted and Woburn and evaluation of methods of measuring soil potassium

BY A. E. JOHNSTON AND T. M. ADDISCOTT

Rothamsted Experimental Station, Harpenden, Herts

(*Revised MS. received* 11 *January* 1971)

SUMMARY

Measurements made on soils from the Ley–Arable rotation experiments and some of the Classical experiments at Rothamsted and Woburn are described. Values of exchangeable K, equilibrium activity ratio, equilibrium K potential, and buffer capacity are given for each plot. Potassium quantity/intensity relationships measured for each plot showed that no differences in K exchange behaviour have arisen as a result of manuring or of ley or arable treatments. The only fundamental variation was in the quantity of K in the soils. Continuous ley plots, whether given N fertilizer or containing clover, contained much more K than plots carrying crop rotations. In the Classical experiment soils, quantity of K depended largely on manuring.

Potassium uptakes by ryegrass grown on the soils from the various plots are discussed. Potassium uptake was well-related to quantity of K, better so than to the other K parameters. The release of non-exchangeable K to the crop was non-linearly related to the fall in exchangeable K in the soils from the Rothamsted Ley–Arable experiments.

Drying and re-wetting the cropped soils released K in amounts inversely proportional to the amount of K in the *moist* cropped soil. This release of K was unrelated to the original exchangeable K contents of the soils.

INTRODUCTION

In many cropping systems, there is probably now a positive K balance, with more K being applied than is removed, especially where cereal straw or the tops of root crops are ploughed in. Much of this excess K is water-soluble and, provided it is not leached from the plough layer, it will enter into the equilibrium between solution K, exchangeable K and non-exchangeable K. (Exchangeable to neutral N-ammonium acetate unless otherwise stated.) In laboratory experiments lasting 12 weeks, Warren & Johnston (1962*b*) showed that fixation of newly added K in non-exchangeable forms in Rothamsted and Woburn soils depended on the pH of the soil and its moisture content. (See also York, Bradfield & Peech, 1953; Karim & Malek, 1957.) More K remained exchangeable in soils kept moist continuously than those alternatively wetted and dried, and more in acid soils (pH 5–6) than in neutral or calcareous soils (pH 7–8). In the neutral and calcareous soils the amount of added K that remained exchangeable depended on the amount of initially exchangeable K. In some soils, all added K remained exchangeable. Fertilizer K added to such soils and not taken up by the crop is liable to be leached out. Johnston (1971) showed that where this had happened on some soils at Woburn, the plough layer and the subsoil down to 21 in contained the same amount of exchangeable K, but some results of Arnold (1970) suggest that K added to some soils can become non-exchangeable to Ca almost immediately. It is important to know how much of this added K remaining as exchangeable and non-exchangeable K can be recovered by crops, and whether different cropping systems or manuring affect the recovery. Also, we wished to know which laboratory measurements best described the behaviour of initially available K and also the amount of initially non-available K released.

Initially available potassium. That plants differ in their ability to remove K from soils has been shown in both the glasshouse (Arnold, 1962*a*; Addiscott, 1970*a*) and the field (Johnston, Warren & Penny, 1970), emphasizing the arbitrary nature of most extractants for soil K. The amount of K removed by many extractants is related to the K exchangeable to neutral N-ammonium acetate, used by us. This follows from a suggestion by Addiscott (1970*b*) that the ability of an extractant to remove soil K can be equated to a K potential (derived from the quantity/potential relationship) attained when the soil loses K equal to that taken out by the extractant. Consequently, the main measurement made on initially available K was the determination of the quantity/potential relationship (Woodruff, 1955; Barrow, Ozanne & Shaw, 1965), which relates change in the exchangeable K content of a soil to K potential, defined as the free energy associated with replacing one equivalent of K by one equivalent of Ca (Schofield, 1947; Arnold, 1962*b*).

$$\text{K potential, } \Delta\bar{G} = RT \ln a_{\mathrm{K}}/\sqrt{a_{\mathrm{Ca+Mg}}}.$$

From the same measurements, the relationship between change in exchangeable K and activity ratio, $a_{\mathrm{K}}/\sqrt{a_{\mathrm{Ca+Mg}}}$, can also be drawn. This is usually called the quantity/intensity (Q/I) curve (Beckett, 1964). It does not matter greatly which relationship is used, but the quantity/potential curve is often more useful in relating to measurements of K removed from the soil, because the (logarithmic) potential scale is larger in the region of K removal. Both relationships are independent of the plant.

The quantity/potential relationship gives a means of measuring K initially available to particular plants (Arnold, 1962*a*; Addiscott, 1970*c*). When the soil K potential at which the plant ceases to be able to absorb K is known, the quantity of K that can be removed before this potential is reached, which can be read from the quantity/potential relationship, is that available to the plant. Measurements on these soils when related to K uptake by plants in pots in the glasshouse, showed that this potential was −5600 cal/equiv. for ryegrass, −5000 cal/equiv. for lettuce and for potatoes it changed from −4150 cal/equiv. to −4900 cal/equiv. as the plants developed (Addiscott, 1970*a*). Thus more K was initially available to ryegrass than to potatoes or to lettuce.

Release of potassium. Release and uptake of initially non-available K can be assessed for a particular crop as the total K uptake minus initially available K (derived from the quantity/potential relationship). Alternatively, uptake of non-exchangeable K, i.e. total K uptake less exchangeable K, may be used.

In Rothamsted soils, potatoes and lettuce took up no initially non-available K (Addiscott, 1970*a*), whereas ryegrass took up large amounts. Probably the uptake of initially non-available K depends on the ability of the plant to lower the soil K potential to a value at which initially non-available K is released fast enough for the needs of the plant.

Strong acids (Haylock, 1956; McLean, 1961) and H-form cation exchange resins have been used fairly successfully to predict release of non-exchangeable K.

DESCRIPTION OF THE SOILS USED AND THE FIELD EXPERIMENTS

Rothamsted soils were from the Batcombe series, undifferentiated phase, except those from Barnfield, which came from the shallow or eroded phase. The Woburn soils were from the Cottenham series, sandy loam developed in drift over Lower Greensand. The soils, from the plough layer (0–9 in), were taken in February 1967 from the nil, fertilizer (PKNaMg) and farmyard manure (FYM) plots of the Broadbalk, Hoosfield and Barnfield Classical experiments and from the FYM + PKNaMg plot on Barnfield; and from two Classical Barley plots and FYM and K fertilizer plots of the Market Garden experiment at Woburn. Because of the shortage of information on the long-term effects of N fertilizer on soil K behaviour, plots given N in these experiments were avoided. All sequences of one phase of the Rothamsted and Woburn Ley–Arable experiments were sampled at the same time; the half plots with and without FYM were sampled separately.

The Ley–Arable experiments were started at Woburn in 1938 and at Rothamsted in 1949. The Rothamsted experiment is in two parts, one on Highfield where the plots were ploughed out from old grass and one on Fosters field long in continuous arable cropping. All the experiments compare contrasted farming systems, each lasting 3 years, and measure their effects on the yields of following arable test crops. At Rothamsted, winter wheat, potatoes and barley were grown as test crops, and at Woburn, roots and barley. The treatment crops were:

(1) 3 years' grazed ley, Lg, grazed by sheep, Rothamsted and Woburn;
(2) 3 years' lucerne, Lu, cut for hay, Rothamsted and Woburn;
(3) 3 years' cut grass, Cg, cut at silage stage, Rothamsted only;
(4) 3 years' arable with hay, Ah, (*a*) seeds hay, root crop, oats at Rothamsted, (*b*) roots, cereal, seeds hay at Woburn;
(5) 3 years' arable with roots, Ar, roots cereal, roots, Woburn only.

At the start of the Rothamsted experiments, one plot in each block was sown with a grass seeds mixture, reseeded ley (R), and on Highfield, one plot was left with the original sward unploughed, permanent grass (G). The R and G plots sampled were not ploughed between 1949 and 1967. From 1961, the management of the Lg and Cg treatments at Rothamsted was changed to compare grass–clover leys without N (Lc) with all grass leys given N (Ln). At the same time, the R and G plots were halved and the halves managed in the same manner as the Lc and Ln plots respectively, giving Rn and Rc and Gn and Gc leys. (Clovers were allowed to establish naturally in the Rc and Gc leys.) At Woburn, half the plots in each block carry the same crop rotation throughout the experiment (continuous), whereas the other half alternates between ley and arable rotations (alternating).

Initially, the manuring was carefully balanced so that all rotations received the same total amount of fertilizer P and K in each cropping cycle. When the roots test crop was grown, plots were split to test O *v.* FYM, 12 tons/acre at Rothamsted and 15 tons/acre at Woburn. The test was cumulative on quarter plots at Rothamsted and on half plots at Woburn. From 1962, the half plot without FYM received extra fertilizer K. At first, the total amount of K given in each cropping cycle was small (224 lb/acre in 6 years at Rothamsted and 134 lb/acre in 5 years at Woburn) and more K was removed in crops taken from the arable, cut grass and lucerne rotations than was applied. The resulting depletion was later made good with K fertilizer and the basal K dressings were increased and varied to meet the requirements of the crops in each rotation. When the comparison of grass–clover leys (Lc, Rc, Gc) with all grass leys (Ln, Rn, Gn) was started at Rothamsted, it was decided that for every pound of N applied to the all grass leys, 0·83 lb K would be given to both the all grass and the grass–clover leys. This revised manuring has left different amounts of K residues under the different ley and arable cropping systems, as has the different manuring in the Classical experiments. Table 1 shows the amount of K given in each dressing of fertilizer or FYM for the treatments shown in subsequent Tables.

Treatment of soil samples. Samples from the field were slowly dried on paper in the glasshouse. As they dried, grass, large roots and stones were removed where necessary and the soils were sieved in succession through $\frac{1}{2}$ in, $\frac{1}{4}$ in and $\frac{1}{8}$ in square mesh sieves. The soils were dried completely before they were subsampled for the pot experiment and for analysis. The analytical sample was sieved to < 2 mm.

LABORATORY EXPERIMENTS

Quantity/potential (and quantity/intensity) relationships

Soils were shaken for 1 h with 0·01 M-$CaCl_2$ containing KCl from 0·00025 to 0·006 M (according to soil K content) at a 1:10 soil to solution ratio and with 0·01 M-$CaCl_2$ only at soil:solution ratios from 1:10 to 1:250 (occasionally 1:750). The suspensions were centrifuged and the K in the supernatant solutions measured by flame photometry. (Ca + Mg) was measured by EDTA titration. Potassium potentials and activity ratios were calculated thus:

$$\text{K potential} = 2{\cdot}303RT\log_{10} AR,$$

where AR = activity ratio (intensity)

$$= \frac{a_{\mathrm{K}}}{\sqrt{a_{\mathrm{Ca+Mg}}}} = \frac{c_{\mathrm{K}}}{\sqrt{c_{\mathrm{Ca+Mg}}}}\frac{f^{+}}{\sqrt{f^{++}}},$$

where f^{+} and f^{++} are the activity coefficients of monovalent and divalent ions. $f^{+}/\sqrt{f^{++}}$ was taken was 1·18 because the value varied little from this within the range of K and (Ca + Mg) concentrations found (Beckett, 1965). Change in exchangeable K content of the soil ($\pm\Delta$K) was calculated from the loss or gain of K by the solution.

Equilibrium K potentials ($\Delta\bar{G}_{\mathrm{o}}$) and equilibrium activity ratios (AR_{o}), at which the soils neither gain nor lose K, were interpolated from the quantity/potential and quantity/intensity relationships.

Exchangeable potassium. 6·25 g of soil was shaken with about 150 ml of neutral N-ammonium acetate in six aliquots. The filtered solution was made to 250 ml and K measured by flame photometry.

Particle size distribution was determined by the 'international' method (I.S.S.S., 1934).

Soil pH was measured in water and 0·01 M-$CaCl_2$ using a 1:2·5, soil:water ratio.

Results

Table 2 shows the following analytical results for the soils:

(1) Soil pH;
(2) exchangeable potassium, K_e;
(3) K removable from each soil before the potential falls to −5600 cal/equiv., the uptake potential for ryegrass, K_{5600};
(4) equilibrium activity ratio, AR_{o};
(5) equilibrium K potential $\Delta\bar{G}_{\mathrm{o}}$;
(6) K buffer capacity, BC_{o}, the tangent to the quantity/intensity curve at the point where the soil neither gains nor loses K (Addiscott & Talibudeen, 1969).

Table 2 also gives K uptakes in the pot experiment, which are discussed in the next section, and exchangeable K measurements in the moist and dried cropped soils.

Quantity/intensity (*Q/I*) *relationships.* Quantity/potential or quantity/intensity relationships provide a means of comparing *K exchange behaviour* in different soils. It does not matter which is used, but quantity/intensity relationships, which have usually been used for inter-comparisons (Beckett, Craig, Nafady & Watson, 1966; Beckett & Nafady, 1967; Addiscott, 1970*d*), were used in this context.

Table 1. *Recent potassium manuring* of the soils from which samples were taken*

Experiment	Fertilizer – K (lb K/acre)	FYM-K (per acre) Dressing	lb K in dressing
Broadbalk 1843–1967	80 lb/year	14 tons/year	145
Hoosfield 1852–1967	80 lb/year		
Barnfield 1843–1967	200 lb/year		
Woburn Continuous Barley			
1877–1906	80 lb/year		
1907–26	22 lb/year		
Woburn Market Garden			
1942–60	44 lb/year	20 tons/crop	380
1961–7	279 lb/year		
Rothamsted Ley Arable			
1949–54	224 lb/6 years according to rotation, e.g. Ln 1145 lb/6 years	12 tons once in 6 years	210
1961–7			
Woburn Ley Arable			
1938–42	134 lb/5 years according to rotation, e.g. Ah 595 lb/5 years	15 tons once in 5 years	280
1964–7			

* For fuller details of manuring histories see: Broadbalk: Johnston & Garner, 1969; Hoosfield: Warren & Johnston, 1967; Barnfield: Warren & Johnston, 1962*a*; Woburn Market Garden, Rothamsted and Woburn Ley Arables: Rothamsted Experimental Station, 1970.

Soils from the Rothamsted Classical experiments and the Classical Barley and Market Garden experiments have similar Q/I relationships within each experiment (Addiscott, 1970*d*). Samples taken from the Broadbalk experiment showed that Q/I relationships of manured and unmanured plots did not change during 100 years (Addiscott, 1970*e*). In the Rothamsted Ley–Arable experiments (Fig. 1 *a–d*) the Q/I curves for the 1967 samples were superimposable (by eye) within each experiment, both mutually and on the Q/I curves of samples taken in 1956. Soils from Highfield and Fosters field, which do not differ greatly in their percentages of clay and which are on the same phase as the Batcombe series, had similar Q/I curves. The Ley–Arable Q/I curves were most similar to (but slightly less steep than) the curves for Broadbalk and Hoosfield, which are on the same phase of the Batcombe series.

At Woburn, soils from the Ley–Arable experiment also differed little in their Q/I relationships (Fig. 1*e*). The other Woburn soils, from the Classical Barley and Market Garden experiments, had Q/I curves that differed slightly from each other and from those of the Ley–Arable experiment (Addiscott, 1970*d*). Determination of the particle size distribution in these Woburn soils showed that those from the Classical Barley and Market Garden experiments had 11·7 and 11·0% clay respectively but those from the Ley–Arable experiment had 14·4% clay.

In none of the experiments do the different cropping systems seem fundamentally to have affected the *exchange behaviour* of K. Ley and arable rotations might be expected mainly to alter the organic matter percentage in soils, but K:Ca exchange as measured by the Q/I relationship seems to occur mainly on the 'mineral' fraction of the soil (Addiscott, 1970*e*).

Other potassium parameters. In view of the uniformity of the Q/I relationships within each experiment, differences in the various K parameters shown in Table 2 probably arise simply as a result of variations in *quantity* of K in the soils.

For example, in the Broadbalk soils the K buffer capacity, BC_o, was related to the K saturation of the mineral *CEC* (K_e/CEC_m), such that

$BC_o = 60 - 250$ (K saturation), $r^2 = 0{\cdot}95$ (Addiscott, 1970*e*), and a fairly similar relationship

$BC_o = 67 - 286$ (K saturation), $r^2 = 0{\cdot}60$,

existed for the Rothamsted Ley–Arable soils, but accounted for less variation.

Potassium in the soils after exhaustive glasshouse cropping

The Ley–Arable soils were cropped for 608 days; the Classical experiment soils are still being cropped (see next section). All the Ley–Arable soils contained appreciable amounts of exchangeable K at the end of the experiment, even before drying. More was released on drying. Table 3 shows mean values of the K potential (measured by Talibudeen & Dey's (1968) short method) and exchangeable K in the moist soil and of exchangeable K after drying the moist soil. The Rothamsted values are comparable with others from Rothamsted soils cropped exhaustively in the glasshouse Talibudeen & Dey (1968) found on prolonged cropping that the

Table 2 (*a*). *Soil and crop results, Rothamsted and Woburn Classical soils**

Experiment	Plot	Manuring	pH in Water	pH in 0·01 M-$CaCl_2$	K_e m-equiv./100 g	K_{5600} m-equiv./100 g	AR_o ($\times 10^3$) $(m/l)^{\frac{1}{2}}$	$-\Delta\bar{G}_o$ (cal/equiv.)	BC_o (m-equiv./100 g) $(m/l)^{-\frac{1}{2}}$	K in ryegrass Cuts 1–3 m-equiv./100 g	K in ryegrass Cuts 1–9 m-equiv./100 g
Rothamsted											
Broadbalk 1843–1967,	3	None	8·0	7·6	0·252	0·293	1·7	3530	77·2	0·413	0·812
winter wheat	5	PKNaMg	8·0	7·5	0·861	1·058	15·3	2370	32·9	1·369	2·160
	2B	FYM	7·6	7·2	1·662	2·032	48·8	1750	9·9	2·123	3·149
Hoosfield 1852–1967,	1/0	None	8·0	7·5	0·253	0·223	1·1	4000	101·0	0·295	0·463
barley	4/0	PKNaMg	7·3	6·8	1·051	1·217	20·7	2305	24·3	1·565	2·507
	7/2	FYM	7·0	6·6	1·782	1·940	51·4	1780	20·2	1·984	3·308
Barnfield 1843–1967,	8/0	None	8·0	7·6	0·435	0·512	2·4	3470	121·0	0·741	1·095
root crops (mangolds)	4/0	PKNaMg	8·1	7·6	1·884	2·640	35·6	1970	25·6	2·572	4·528
	1/0	FYM	7·7	7·3	1·456	1·870	17·0	2375	48·7	2·111	3·385
	2/0	FYM + PKNaMg	7·7	7·3	2·851	3·670	57·5	1650	22·9	2·640	5·250
										(0·147)	(0·111)
										L.S.D. (5%)	
Woburn											
Continuous Barley†	1	None	6·2	5·9	0·149	0·155	3·2	3425	29·4	0·310	0·378
1877–1926	4	PK	6·7	6·2	0·157	0·167	3·6	3365	26·9	0·302	0·380
Market Garden‡	75	FYM + PK	6·6	6·1	1·129	1·254	71·0	1565	10·6	1·452	2·219
1942–67	76	NPK	6·6	6·3	0·697	0·782	35·0	1980	11·3	1·041	1·551
										(0·080)	(0·080)
										L.S.D. (5%)	

* For details of K manuring see Table 1; of cropping and manuring see: Broadbalk: Johnston & Garner, 1969; Barnfield: Warner & Johnston, 1962*a*; Hoosfield: Warren & Johnston, 1967; Woburn Continuous Barley and Market Garden experiments, Rothamsted Experimental Station (1970).

† This experiment was manured 1876–1926, from 1927 to 1967 P and K was not applied.

‡ Market Garden crops grown included leeks, early potatoes, early carrots, cabbages, peas, red beet.

Table 2 (*b*). *Soil and crop results, Rothamsted Ley Arable soils*

Cropping system	Symbol	pH in Water	pH in 0·01 M-$CaCl_2$	K_e m-equiv./100 g	K_{5600} m-equiv./100 g	AR_o ($\times 10^3$) (m/l)	$-\Delta\bar{G}_o$ (cal/equiv.)	BC_o (m-equiv./100 g) (m/l)$^{-\frac{1}{2}}$	K in ryegrass Cuts 1–3 m-equiv./100 g	K in ryegrass Cuts 1–9 m-equiv./100 g	K_e in cropped soil Moist m-equiv./100 g	K_e in cropped soil Dried m-equiv./100 g
Highfield 1949–67												
Rotations without FYM												
Arable	Ah_o	6·5	6·0	0·424	0·436	4·2	3190	72·2	0·501	0·746	0·083	0·166
Lucerne	Lu_o	6·5	6·1	0·402	0·492	3·8	3350	69·7	0·548	0·832	0·101	0·208
Grass ley with N	Ln_o	6·4	6·0	0·420	0·525	5·1	3060	62·1	0·526	0·750	0·120	0·179
Clover grass ley	Lc_o	6·6	6·1	0·597	0·687	9·3	2770	51·0	0·793	1·168	0·173	0·185
Rotations with FYM												
Arable	Ah_d	6·4	5·9	0·470	0·664	6·5	2865	53·6	0·543	0·809	0·110	0·172
Lucerne	Lu_d	6·3	5·9	0·438	0·555	4·3	3220	70·6	0·598	0·891	0·125	0·198
Grass ley with N	Ln_d	6·3	5·9	0·435	0·494	7·4	2965	32·4	0·614	0·927	0·105	0·191
Clover grass ley	Lc_d	6·5	6·2	0·699	0·878	11·2	2650	46·4	0·935	1·372	0·134	0·205
Continuous grass without FYM												
Reseeded with N	Rn	5·4	5·0	0·895	1·175	16·5	2445	31·6	1·221	1·659	0·146	0·170
Reseeded clover grass	Rc	6·5	6·2	1·796	2·220	47·9	1660	19·2	2·332	3·188	0·153	0·226
Permanent with N	Gn	5·5	5·1	1·121	1·550	22·9	2300	41·9	1·473	2·032	0·113	0·158
Permanent clover grass	Gc	6·6	6·3	1·558	1·884	36·3	1980	34·9	2·043	2·797	—*	—*
								L.S.D. (5%)	(0·119)	(0·117)		
Fosters Field 1949–67												
Rotations without FYM												
Arable	Ah_o	7·8	7·3	0·412	0·528	4·4	3055	57·3	0·609	0·907	0·124	0·181
Lucerne	Lu_o	7·8	7·4	0·441	0·553	4·3	2990	56·0	0·625	0·884	0·137	0·181
Grass ley with N	Ln_o	7·6	7·2	0·518	0·570	6·2	3030	51·6	0·783	1·009	0·143	0·182
Clover grass ley	Lc_o	7·7	7·3	0·584	0·750	9·8	2670	38·8	0·929	1·280	0·106	0·179
Rotations with FYM												
Arable	Ah_d	7·8	7·4	0·471	0·697	6·8	2900	46·5	0·785	1·170	0·109	0·192
Lucerne	Lu_d	7·8	7·4	0·419	0·415	4·0	3060	58·4	0·608	0·871	0·128	0·174
Grass ley with N	Ln_d	7·7	7·3	0·496	0·588	5·5	3000	54·0	0·689	0·931	0·154	0·211
Clover grass ley	Lc_d	7·6	7·3	0·877	0·970	16·7	2370	38·9	1·180	1·655	0·142	0·182
Continuous grass without FYM												
Reseeded with N	Rn	5·7	5·6	0·870	0·863	17·5	2330	35·3	1·008	1·453	0·104	0·184
Reseeded clover grass	Rc	6·4	6·1	1·354	1·724	32·7	2000	27·9	1·625	2·317	—*	—*
								L.S.D. (5%)	(0·097)	(0·077)		

* Pot not dismantled, grass left growing.
For cropping and manuring see Rothamsted Experimental Station, 1970.

Table 2 (c). *Soil and crop results, Woburn Ley Arable soils*

Cropping system	Symbol	pH in water	pH in 0·01 M-$CaCl_2$	K_e (m-equiv./100 g)	K_{5600} (m-equiv./100 g)	AR_o ($\times 10^3$) $(m/l)^{\frac{1}{2}}$	$-\Delta\bar{G}_o$ (cal/equiv.)	BC_o (m-equiv./100 g) $(m/l)^{-\frac{1}{2}}$	K in ryegrass, Cuts 1–3 (m-equiv./100 g)	K in ryegrass, Cuts 1–9 (m-equiv./100 g)	K_e in cropped soil, Moist (m-equiv./100 g)	K_e in cropped soil, Dried (m-equiv./100 g)
Woburn 1938–67												
Continuous rotations without FYM												
Arable with hay	Ah_o	6·0	5·6	0·367	0·452	11·4	2595	21·0	0·663	0·912	0·068	0·098
Arable with roots	Ar_o	6·7	6·3	0·315	0·379	8·0	2810	26·5	0·620	0·887	0·063	0·104
Lucerne	Lu_o	6·5	6·1	0·438	0·560	13·3	2575	22·8	0·911	1·276	0·063	0·119
Grazed ley	Lg_o	6·2	5·7	0·482	0·828	19·7	2360	20·9	0·918	1·271	0·075	0·091
Continuous rotations with FYM												
Arable with hay	Ah_d	6·3	5·9	0·431	0·503	11·3	2635	25·1	0·820	1·138	0·076	0·119
Arable with roots	Ar_d	6·4	6·1	0·391	0·454	10·4	2685	24·3	0·822	1·132	0·073	0·123
Lucerne	Lu_d	6·3	5·8	0·486	0·695	13·7	2520	23·2	0·930	1·263	0·091	0·124
Grazed ley	Lg_d	6·2	5·7	0·482	0·770	17·5	2410	20·0	0·961	1·266	0·079	0·093
Alternating* rotations without FYM												
Arable with hay	(Ah_o)	6·4	6·1	0·444	0·650	13·0	2580	26·3	0·866	1·207	0·085	0·114
Arable with roots	(Ar_o)	6·7	6·2	0·362	0·417	9·2	2790	23·1	0·697	0·932	0·052	0·096
Lucerne	(Lu_o)	6·6	6·1	0·410	0·503	9·8	2750	28·7	0·901	1·263	0·087	0·120
Grazed ley	(Lg_o)	5·9	5·5	0·440	0·635	12·4	2605	27·0	0·788	1·103	0·062	0·102
Alternating rotations with FYM												
Arable with hay	(Ah_d)	6·4	6·0	0·377	0·402	8·3	2825	31·6	0·687	0·909	0·091	0·110
Arable with roots	(Ar_d)	6·4	6·1	0·332	0·412	8·8	2800	25·3	0·625	0·858	0·049	0·087
Lucerne	(Lu_d)	6·2	5·8	0·429	0·650	13·3	2560	27·2	0·872	1·176	0·071	0·115
Grazed ley	(Lg_d)	6·2	5·7	0·500	0·733	13·5	2540	26·3	0·893	1·227	0·075	0·097
L.S.D. (5%)									(0·055)	(0·055)		

* In each block of the experiment half of the plots always have the same treatment rotation (continuous), whilst on the other half ley and arable treatment rotations alternate, e.g. Lu, test, Ah, test, Lg, test, Ar, test (alternating).

For cropping and manuring see details of the Classical and Long-Term Experiments up to 1967, Rothamsted Experimental Station (1970).

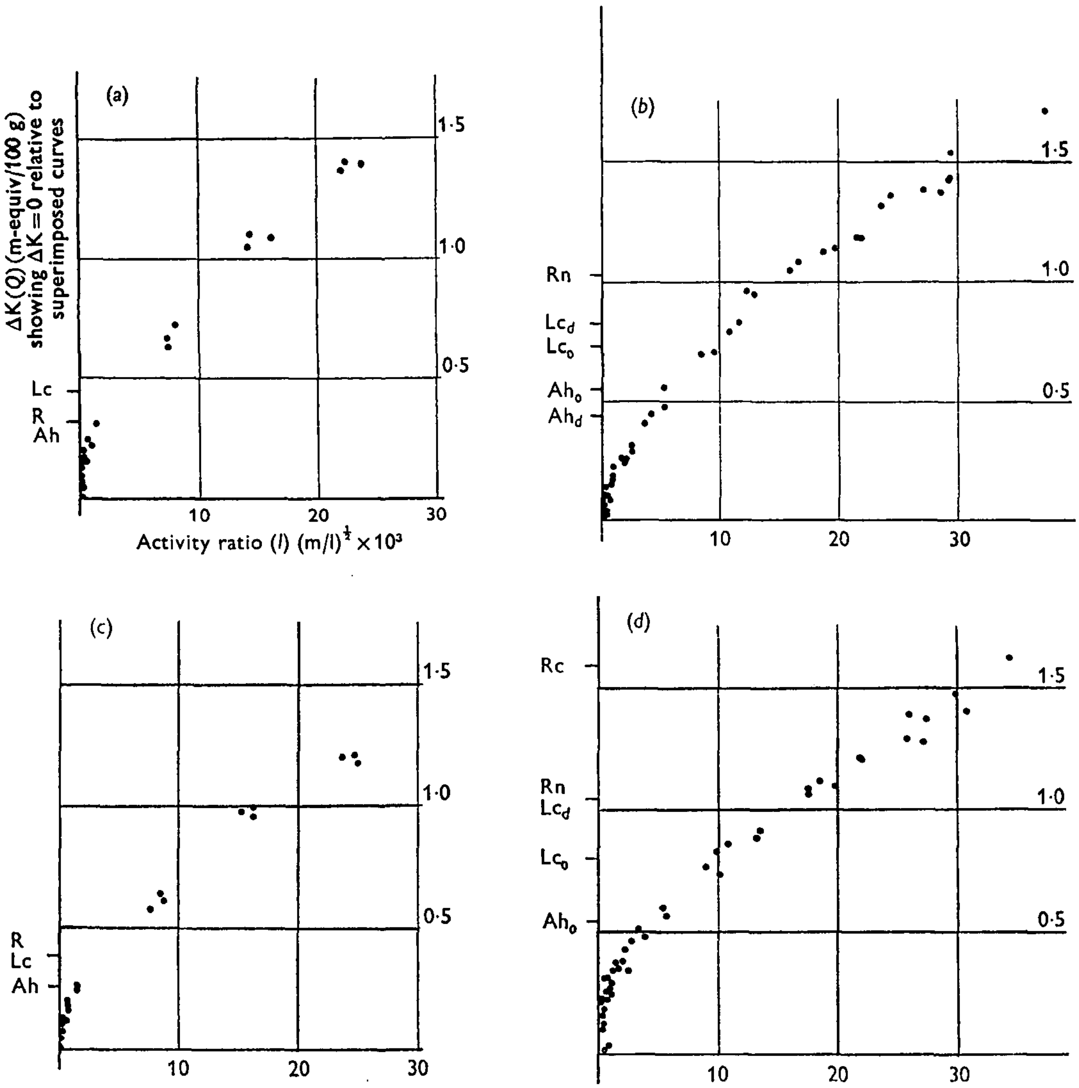

Fig. 1. The superimposed Q/I curves for Ley-Arable experiments in Highfield; (*a*) 1956, (*b*) 1967, Fosters, (*c*) 1956, (*d*) 1967, and at Woburn, (*e*) 1967.

activity ratio did not fall much below $3-7\times10^{-4}$ $(m/l)^{\frac{1}{2}}$, i.e. the potential below -4790 to -4290 cal/equiv. Arnold & Close (1961) showed either that ryegrass would not grow in Agdell soils unless there was 0·13 m-equiv./100 g exchangeable K, or that all soils were eventually depleted to a common level of 0·13 m-equiv./100 g exchangeable K. In our experiments, exchangeable K contents in the moist and dried cropped soils were not related to each other. Potassium released when the cropped soils were dried was not related to exchangeable K at the start of the experiment, but it was significantly related to exchangeable K in the moist cropped soil from all three Ley-Arable experiments, such that the more exchangeable K there was, the less was released. The regressions:

for Highfield,

K released $= 0{\cdot}155-(0{\cdot}740\pm0{\cdot}253)$ (K in moist cropped soil);

for Fosters,

K released $= 0{\cdot}154-(0{\cdot}758\pm0{\cdot}209)$ (K in moist cropped soil);

and for Woburn,

K released $= 0{\cdot}070-(0{\cdot}488\pm0{\cdot}222)$ (K in moist cropped soil);

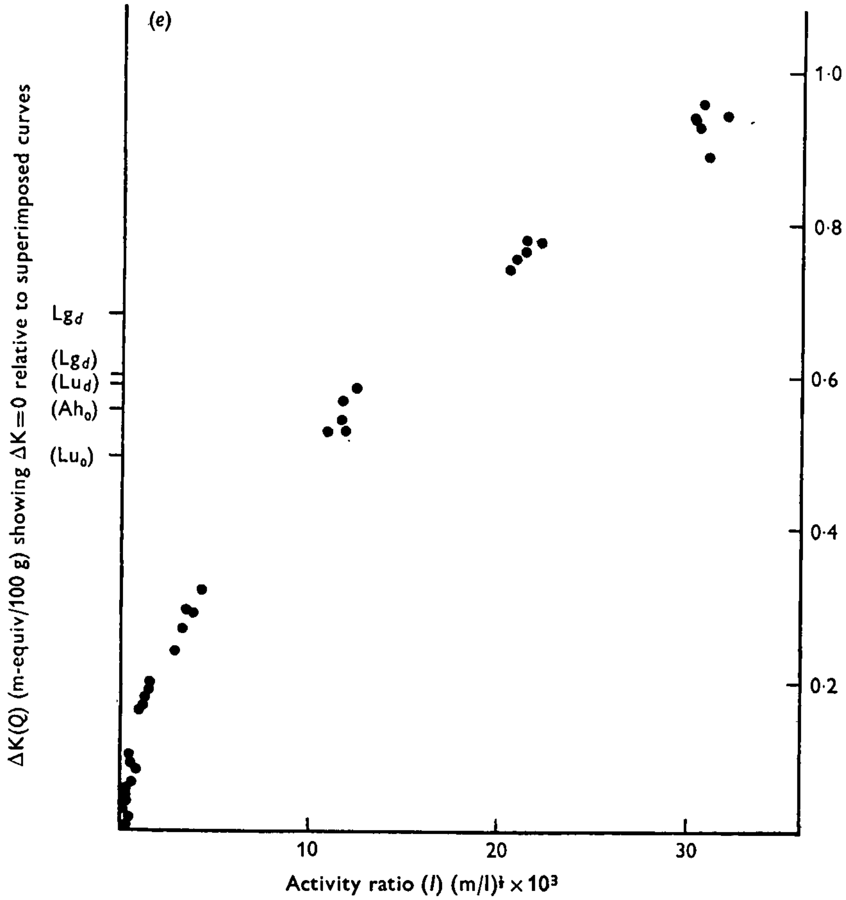

Fig. 1(*e*). For legend see opposite.

Table 3. *Mean values of potassium potential and exchangeable potassium in moist cropped soil and of exchangeable potassium after drying. Rothamsted and Woburn Ley–Arable soils*

	K potential in moist soil (cal/equiv.)	Exchangeable K (m-equiv./100 g) in moist soil	Exchangeable K (m-equiv./100 g) after drying moist soil
Highfield	−5010	0·12	0·19
Fosters	−5410	0·13	0·19
Woburn	−5340	0·07	0·11

show how much exchangeable K must apparently be left in the moist cropped soil for no more to be released during a drying and wetting cycle. The values 0·210 and 0·204 m-equiv./100 g dry soil for the Highfield and Fosters experiments are fairly similar to the amounts of exchangeable K in the unfertilized plots in the Broadbalk and Hoosfield experiments, both on the same phase of the Batcombe series (both 0·25 m-equiv/100 g), and the Woburn value (0·144 m-equiv./100 g) to the exchangeable K in the Classical Barley plots (0·15 and 0·16 m-equiv./100 g).

These values may correspond to the 'equilibrium K saturation' measured by De Turk, Wood & Bray (1943), Matthews & Sherrell (1960) and Matthews & Beckett (1962).

POT EXPERIMENT

The pot experiment was made with four replicates of each of the 52 soils, one replicate in each of four randomized blocks. 400 g of soil (air-dry, < $\frac{1}{8}$ in) and 200 g of quartz (> 2 mm) for each pot were moistened and well mixed. Perennial ryegrass (0·5 g per pot) was sown. Basal nutrients N, P and Mg at 100, 50 and 10 mg per pot were given at the start and 25 mg P and 5 mg Mg after the fourth cut. Fifty mg N per pot was given at intervals during the experiment. The grass was cut after 28, 54, 82, 118, 153, 209, 307, 421 and 608 days, dried and weighed and then analysed for K by extracting with cold 0·5 N-HCl. Cumulative K uptakes were calculated.

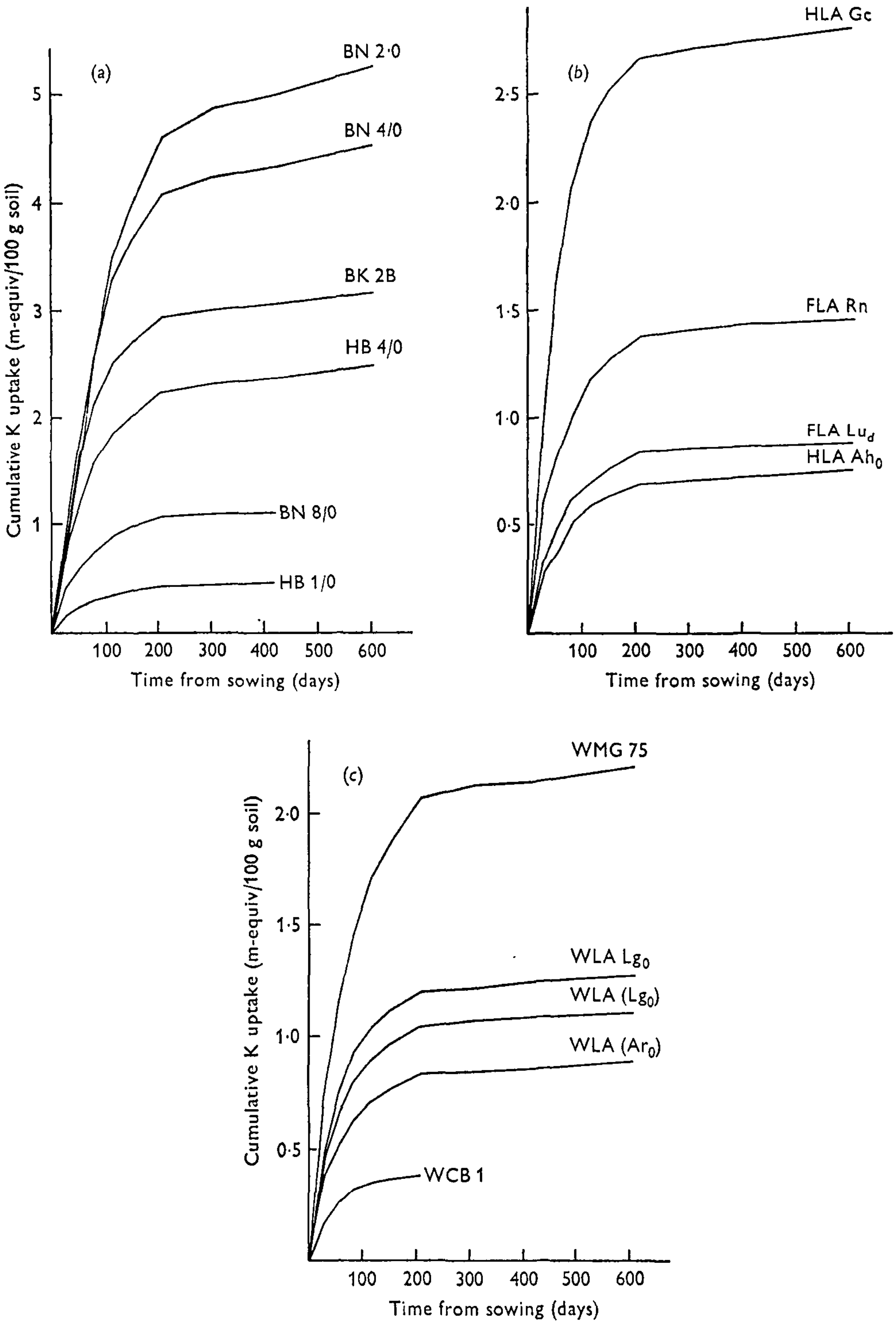

Fig. 2. Cumulative K uptakes plotted against time for some soils from: (*a*) Barnfield (BN), Broadbalk (BK) and Hoosfield (HB); (*b*) Ley–Arable experiments in Highfield (HLA) and Fosters (FLA); (*c*) Woburn Market Garden (WMG) and Ley–Arable (WLA) and Classical Barley (WCB) experiments.

After these nine cuts, the results (Fig. 2) suggested that little more K would be taken up and the experiment was not continued, except for the soils from the Classical experiments and the Highfield Gc and Fosters Rc plots. The soils were separated as well as possible from the roots and sieved to remove the quartz (> 2 mm). They were stored moist until exchangeable K and the K potential were determined, the latter by Talibudeen & Dey's (1968) short method (see previous section). The roots were not analysed because they could not be retained complete, and the results of Arnold & Close (1961) suggested that they would contain only a small proportion of the total K uptake.

Results

Cumulative K uptake is shown plotted against time for some of the Rothamsted (Fig. 2*a*, *b*) and Woburn (Fig. 2*c*) soils. The shapes of these curves varied little. A large proportion of the K had always been taken up by the fifth cut (153 days), only a quarter of the way through the experiment. For the Rothamsted and Woburn Ley–Arable soils this proportion was always between 84 and 90%, but it varied more for the soils from the Classical experiments.

Talibudeen & Dey (1968) cropped some of the soils used from the Classical experiments, but for a maximum of 60 as compared with 87 weeks in our experiment. Uptakes were 13–21% larger than in their experiment, except for the Hoosfield unfertilized plot, where their cropping removed 4% more K, but this soil was exhausted before the end in both experiments.

Potassium uptakes: Classical experiment soils. Table 2 shows the total K uptake by the grass and that in cuts 1–3 separately. For the soils from the Rothamsted and Woburn Classical experiments, cumulative K uptakes were greater from soils with many dressings of fertilizer K or FYM. Soils given FYM only, on Broadbalk, Hoosfield and Barnfield, yielded much the same amount of K, 3·150, 3·309 and 3·385 m-equiv./100 g soil respectively. Soils with fertilizer K only yielded 2·160 and 2·508 m-equiv./100 g soil on Broadbalk and Hoosfield, where the annual dressing for 104 years has been 80 lb K/acre, but 4·528 m-equiv./100 g on Barnfield where for 90 years 200 lbK/acre has been given. The grass extracted the most K (5·250 m-equiv./100 g soil) from the Barnfield soil which gets FYM + K fertilizer (200 lb K/acre) each year. Of the unfertilized plots, that on Barnfield, which has the largest percentage of clay, yielded most K, followed by Broadbalk and Hoosfield. We do not know why uptake from the Broadbalk soil so greatly exceeded that from the Hoosfield soil.

Potassium uptakes: Ley–Arable soils. In the Rothamsted Ley–Arable soils, cumulative K uptakes in the grass-clover (Rc, Gc) leys of the reseeded (R) and permanent grass (G) leys were largest, about the same as in K fertilizer plots of the Classical experiments (Tables 2*a*, *b*). Soils from the corresponding Rn and Gn leys yielded less K. Cumulative K uptakes from soils under ley and arable rotations were always smaller than from the soils under the continuous grass leys (Rn, Rc, Gn, Gc), though the grass-clover ley soils (Lc) yielded more than did the remaining three soils (Ah, Lu, Ln), which gave similar K uptakes.

Cumulative K uptakes from the Woburn Ley–Arable soils (Table 2*c*) were about the same for all cropping treatments; they were slightly larger than those from the ley and arable rotation soils at Rothamsted, but smaller than those from the Rothamsted soils under continuous grass. The Woburn Ley–Arable soils should have differed little because, in 1961 and in 1966, appropriate amounts of K were added to give all the soils the same amount of exchangeable K.

Total K uptakes from Rothamsted and Woburn Ley–Arable soils with and without FYM are shown in Table 4, with least significant differences ($P < 0.05$). At Rothamsted, soils with FYM yielded significantly more K than those without for the Ln and Lc plots on Highfield and the Ah and Lc plots on Fosters field; differences on the other

Table 4. *Comparison of total potassium uptakes from soils given FYM (d) and fertilizer (f)*, Rothamsted and Woburn Ley–Arable experiments*

		d	*f*	*d* − *f*
Highfield	Ah	0·81	0·75	+0·06
	Lu	0·89	0·83	+0·06
	Ln	0·93	0·75	+0·18
	Lc	1·37	1·17	+0·20
				L.S.D. (5%) 0·117
Fosters	Ah	1·17	0·91	+0·26
	Lu	0·87	0·88	−0·01
	Ln	0·93	1·01	−0·08
	Lc	1·66	1·28	+0·38
				L.S.D. (5%) 0·077
Woburn	Ar	1·13	0·89	+0·24
	Ah	1·14	0·91	+0·23
	Lu	1·26	1·28	−0·02
	Lg	1·27	1·27	−0·00
	(Ar)	0·86	0·93	−0·07
	(Ah)	0·91	1·21	−0·30
	(Lu)	1·18	1·26	−0·08
	(Lg)	1·23	1·10	+0·13
				L.S.D. (5%) 0·055

* Compensatory K fertilizer dressings corresponding to the K given in the FYM dressings were given on the last occasion at Rothamsted and the last two at Woburn.

plots were small or non-significant. Only three dressings of FYM (5 on the Ah rotations) were given at Rothamsted, and as on the last occasion extra K fertilizer was given to the half plots without FYM, some of the differences were unexpectedly large. At Woburn there seemed to be no consistent pattern. This effect of FYM is discussed further in the next section.

Laboratory and pot experiment results compared

The results gave an opportunity to assess some of the many methods proposed for measuring K availability and to examine the release of 'non-exchangeable K' (Arnold & Close, 1961).

Relating potassium uptake by ryegrass to potassium availability measurements. K uptake in the first three cuts and K uptake in all nine cuts were related to the following measures of K availability:

(1) exchangeable K, K_e;

(2) the amount of K that can be removed before the K potential falls to -5600 cal/equiv., K_{5600}, this should be K initially available to ryegrass;

(3) the equilibrium activity ratio, AR_0;

(4) the equilibrium K potential, $\Delta \bar{G}_0$;

(5) The K buffer capacity, BC_0;

in Rothamsted and Woburn soils and in the soils from both stations taken together.

Table 5 shows that regressions on the *quantity* measurements K_e and K_{5600} usually accounted for more variation in the K uptakes than did regressions on the other K measurements, although the equilibrium K potential was as useful in Woburn soils. The K buffer capacity, BC_0, related poorly to plant uptake.

There was little to choose between K_e and K_{5600}, but this is not unexpected because they were closely correlated. ($r = 0.992$ for Rothamsted soils, 0·930 for Woburn soils, and 0·989 for both together.) K_{5600} was on average 23% larger than K_e in Rothamsted soils and 29% larger in Woburn soils.

Potassium uptakes in the first three cuts and in all nine cuts were also closely correlated with each other ($r = 0.976$ for Rothamsted soils, 0·994 for Woburn soils, and 0·979 for both together), so both periods of K uptake placed the K availability parameters in much the same order.

Table 5. *Percentage of variation in potassium uptakes in first three or all nine cuts accounted for by K_e, K_{5600}, AR_0, $\Delta\bar{G}_0$ and BC_0*

	K_e	K_{5600}	AR_0	$\Delta\bar{G}_0$	BC_0
Rothamsted					
First three cuts	93	93	84	82	48
All nine cuts	95	96	80	72	41
Woburn					
First three cuts	86	89	65	90	44
All nine cuts	91	88	73	92	49
Rothamsted and Woburn together					
First three cuts	92	92	68	71	15
All nine cuts	95	95	65	61	11

The good relationships between K uptake and quantity of K (K_e or K_{5600}) suggest that differences in K uptake between corresponding Highfield and Fosters plots, between rotations and continuous grass leys, or between plots with and without FYM, were usually attributable to differences in quantity of K.

Uptake of non-exchangeable or initially non-available potassium by ryegrass. In soils on the *same parent material* where exchangeable and non-exchangeable K have time to come to equilibrium, the two categories of K should be well related to each other (e.g. Reitmeier, 1951; Arnold & Close, 1961). The K uptake in the first three cuts was well related to that in all nine, and both were well related to K_e and K_{5600}, suggesting that the two categories were related. Arnold & Close (1961) related release of non-exchangeable K to fall in exchangeable K for a Saxmundham soil, where

$$\text{fall in } K_e = K_e - (\text{exchangeable K in cropped soil})$$

and

$$\text{release of non-exchangeable K} = (\text{total K uptake}) - (\text{fall in } K_e)$$

In the present experiments, this could only be done for the Ley–Arable soils, because only for these has K_e in the cropped soil yet been determined; the other soils are still growing grass. The value of K_e in the *moist* cropped soil was used.

For the Highfield and Fosters soils, release of non-exchangeable K was related to fall in K_e with an almost sigmoid relationship (Fig. 3*a*). When release of 'initially non-available K' was calculated similarly, substituting K_{5600} for K_e, release of initially non-available K was also non-linearly related to fall in K_{5600} (Fig. 3*b*) and varied little relative to variations in the fall in K_{5600}.

The relationships on Fig. 3 (*a*,*b*) differ only because non-exchangeable K was derived by subtracting K_e from ($K_p + K_e$ in cropped soil) whilst initially non-available K was derived by subtracting K_{5600}; K_{5600} was always larger than K_e. The relationships may be explicable if there are different categories of non-exchangeable K (cf. Reitmeier, 1951; Arnold & Close, 1961), one of which (say K_x) was in equilibrium with and tended to vary with K_e. Our results do not show how much of each category is included in K_p, but K_{5600} must have included part of K_x, so that initially non-available K includes less of K_x than does non-exchangeable K and so varies less with fall in K_{5600} than non-exchangeable K does with fall in K_e. A less empirical explanation of Fig. 3 does not seem possible at present.

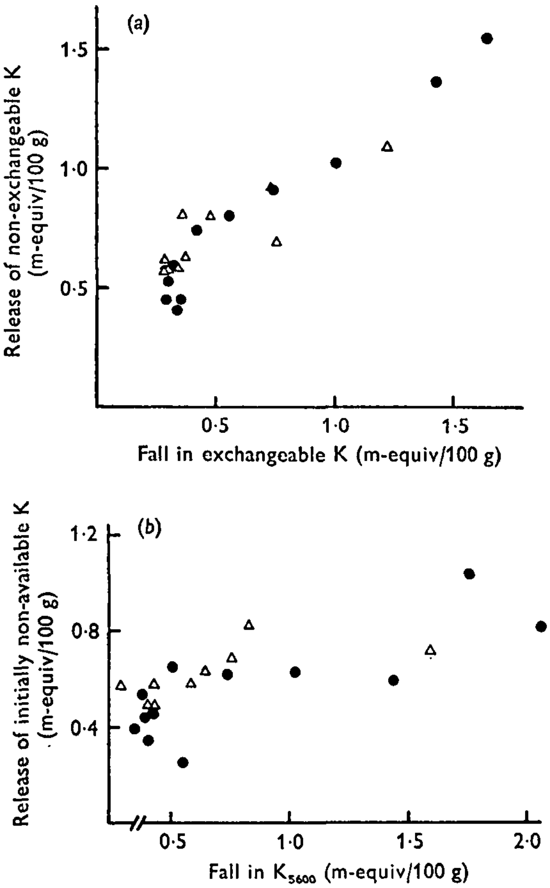

Fig. 3. (*a*) Release of non-exchangeable K plotted against fall in exchangeable K. (*b*) Release of initially non-available K plotted against fall in K_{5600}. ● Highfield, △ Fosters, Ley–Arable experiments.

The Woburn Ley–Arable soils differ little in their K content, and differences in release of non-exchangeable or initially non-available K, and in fall in K_e or K_{5600}, were too small to show the nature of the relationship.

DISCUSSION

The results of the laboratory measurements do not suggest any differences in K behaviour between soils under various ley and arable croppings, other than those arising from differences in the *quantity* of K in the soil.

All the K availability parameters are related, mostly non-linearly, to quantity of K in the soil, so K uptake by the ryegrass would be related ultimately to quantity of K. However, the results of the pot experiment show that K uptake seemed best related *directly* to quantity of K in the Rothamsted soils, and equally well related to quantity or potential of K in the Woburn soils. The close relationship between K_e and K_{5600} suggests that, for soils from the same parent materials, there is probably little difference in value between different quantity measurements (see also Addiscott, 1970*b*).

The K taken up during all nine cuts represents the results of stressing the soils much more than would be usual in the field. Even this K uptake was well related to measurements nominally of initially exchangeable or available K. Thus, except for soils in which K is released much faster than at Rothamsted or Woburn, simple quantity measurements, such as exchangeable K, should be adequate to give advice on K availability even though they underestimate the actual amount of K available to ryegrass. Such measurements alone cannot fully predict probable response to fresh dressings of K.

The following paper (part 2) suggests how the differences in quantity of K in the different ley and arable treatments may have arisen.

We thank those members of the Chemistry Department who helped with the glasshouse and analytical work and J. H. A. Dunwoody for the statistical analysis.

REFERENCES

Addiscott, T. M. (1970*a*). *Rep. Rothamsted exp. Stn for* 1969, p. 63.

Addiscott, T. M. (1970*b*). Use of the quantity/potential relationship to provide a scale of the ability of extractants to remove soil potassium. *J. agric. Sci., Camb.* **74**, 119–21.

Addiscott, T. M. (1970*c*). The uptake of initially available soil potassium by ryegrass. *J. agric. Sci., Camb.* **74**, 123–9.

Addiscott, T. M. (1970*d*). The potassium *Q/I* relationships of soils given different K manuring. *J. agric. Sci., Camb.* **74**, 131–7.

Addiscott, T. M. (1970*e*). Potassium:calcium exchange in soils of the Broadbalk experiment at Rothamsted. *J. agric. Sci., Camb.* **75**, 451–7.

Addiscott, T. M. & Talibudeen, O. (1969). The buffering capacity of potassium reserves in soils. *Potash Rev. Subject* 4, 45*th suite*, pp. 1–24.

Arnold, P. W. (1962*a*). Soil potassium and its availability to plants. *Outl. Agric.* **3**, 263–7.

Arnold, P. W. (1962*b*). The potassium status of some English soils considered as a problem of energy relationships. *Proc. Fertil. Soc.* **72**, 25–43.

Arnold, P. W. (1970). The behaviour of potassium in soils. *Proc. Fertil. Soc.* **115**, 3–15.

Arnold, P. W. & Close, B. M. (1961). Potassium releasing power of soils from the Agdell rotation experiments assessed by glasshouse cropping. *J. agric. Sci., Camb.* **57**, 381–6.

Barrow, N. J. Ozanne, P. G. & Shaw, T. C. (1965). Nutrient potential and capacity. I. The concepts of nutrient potential and capacity and their application to soil potassium and phosphorus. *Aust. J. agric. Res.* **16**, 61–76.

Beckett, P. H. T. (1964). Studies on soil potassium. II. The immediate *Q/I* relations of labile potassium in the soil. *J. Soil Sci.* **15** (1), 9–23.

Beckett, P. H. T. (1965). Activity coefficients for studies on soil potassium. *Agrochimica* **9** (2), 150–2.

Beckett, P. H. T., Craig, J. B., Nafady, M. H. M. & Watson, J. P. (1966). Studies on soil potassium. V. The stability of *Q/I* relations. *Pl. Soil* **25** (3), 435–55.

Beckett, P. H. T. & Nafady, M. H. M. (1967). Studies on soil potassium. VI. The effect of K fixation and release on the form of the K:Ca+Mg exchange isotherm. *J. Soil Sci.* **18** (2), 244–62.

De Turk, E. E., Wood, L. K. & Bray, R. H. (1943). Potash fixation in corn-belt soils. *Soil Sci.* **55**, 1–12.

Haylock, O. F. (1956). A method for estimating the availability of non-exchangeable potassium. *Proc. 6th Int. Congr. Soil Sci.* B, 403–8.

I.S.S.S. (1934). *Trans 1st Comm. Int. Soc. Soil Sci.* pp. 303–5.

Johnston, A. E. (1971). Potassium residues in soils from experiments at Rothamsted and Woburn. In *Residual values of applied nutrients. Tech. Bull. Minist. Agric. Fish Fd* no. 20, .

Johnston, A. E. & Garner, H. V. (1969). The Broadbalk wheat experiment: historical introduction. *Rep. Rothamsted exp. Stn for* 1968, pt 2, pp. 12–25.

Johnston, A. E., Warren, R. G. & Penny, A. (1970). The value of residues from long period manuring at Rothamsted and Woburn. V. The value to arable crops of residues accumulated from potassium fertilisers. *Rep. Rothamsted exp. Stn for* 1969, pt 2, pp. 69–90.

Karim, A. Q. M. B. & Malek, M. A. (1957). Potassium fixation in East Pakistan soils under different conditions. *Soil Sci.* **83**, 229–38.

MacLean, A. J. (1961). Potassium supplying power of some Canadian soils. *Can. J. Soil Sci.* **41**, 196–206.

Matthews, B. C. & Beckett, P. H. T. (1962). A new procedure for studying the release and fixation of potassium ions in soil. *J. agric. Sci., Camb.* **58**, 59–64.

Matthews, B. C. & Sherrell, C. G. (1960). Effect of drying on exchangeable potassium of Ontario soils and the relation of exchangeable potassium to crop yield. *Can. J. Soil. Sci.* **40**, 35–41.

Reitmeier, R. F. (1951). Soil potassium. *Adv. Agron.* **3**, 113–64.

Rothamsted Experimental Station (1970). *Details of the Classical and Long-term Experiments up to* 1967. 128 pp. Harpenden.

Schofield, R. K. (1947). A ratio law governing the equilibrium of cations in the soil solution. *Proc. 11th Int. Cong. pure appl. Chem., London* **3**, 257–61.

Talibudeen, O. & Dey, S. K. (1968). Potassium reserves in British soils. I. The Rothamsted classical experiments. *J. agric. Sci., Camb.* **71**, 95–104.

Warren, R. G. & Johnston, A. E. (1962*a*). Barnfield. *Rep. Rothamsted exp. Stn for* 1961, pp. 227–47.

Warren, R. G. & Johnston, A. E. (1962*b*). The accumulation and loss of soil potassium in long term experiments at Rothamsted and Woburn. *Proc. Fertil. Soc.* **72**, 1–24.

Warren, R. G. & Johnston, A. E. (1967). Hoosfield Continuous Barley. *Rep. Rothamsted exp. Stn for* 1966, pp. 320–38.

Woodruff, C. M. (1955). The energies of replacement of calcium by potassium in soils. *Proc. Soil Sci. Soc. Am.* **19**, 167–71.

York, E. J., Bradfield, R. & Peech, M. (1953). Calcium-potassium interactions in soils and plants. I. Lime-induced potassium fixation in Mardin silt loam. *Soil Sci.* **76**, 379–87.